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14. ABSTRACT Laser cooling of atoms and molecules is an enabling technology for a number of applications, including atomic clocks, navigational sensors and quantum information processing. So far applications of this powerful technique have been limited to a handful of species as the conventional laser cooling requires closed (cycling) transitions. Here we will theoretically investigate the possibility of extending laser cooling techniques to a much wider class of multilevel atoms and molecules. The basic idea is to employ controllable coherent trains of laser pulses (frequency combs). Recently the power and spectral coverage of frequency combs have grown considerably with projected					
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## Report Title

Final report on frequency comb cooling project

### ABSTRACT

Laser cooling of atoms and molecules is an enabling technology for a number of applications, including atomic clocks, navigational sensors and quantum information processing. So far applications of this powerful technique have been limited to a handful of species as the conventional laser cooling requires closed (cycling) transitions. Here we will theoretically investigate the possibility of extending laser cooling techniques to a much wider class of multilevel atoms and molecules. The basic idea is to employ controllable coherent trains of laser pulses (frequency combs). Recently the power and spectral coverage of frequency combs have grown considerably with projected average powers above 10 kW. We will take advantage of this emerging technology. In the first project, we will exploit spectral selectivity of the combs and develop a time sequence protocol to move population across multiple levels with the goal of optimizing Doppler cooling for multi-level systems. In the second project, we will investigate stimulated optical force to slow heteronuclear molecules using ro-vibrational transitions inside the ground electronic state. Further, we propose to apply concepts from quantum-control and learning algorithms for finding optimal pulse sequences for cooling molecules even when the knowledge about their internal structures is imprecise.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
03/18/2014	1.00 Mahmoud Ahmad, Ekaterina Ilinova, Andrei Derevianko. Doppler cooling with coherent trains of laser pulses and a tunable velocity comb, Physical Review A, (09 2011): 33421. doi: 10.1103/PhysRevA.84.033421
03/18/2014	2.00 Ekaterina Ilinova, Andrei Derevianko. Doppler cooling of three-level Lambda systems by coherent pulse trains, Physical Review A, (08 2012): 23417. doi: 10.1103/PhysRevA.86.023417
03/18/2014	3.00 Andrei Derevianko, Ekaterina Ilinova. Dynamics of a three-level Lambda-type system driven by trains of ultrashort laser pulses, Physical Review A, (07 2012): 13423. doi: 10.1103/PhysRevA.86.013423
03/18/2014	5.00 Mahmoud Ahmad, Ekaterina Ilinova, Andrei Derevianko. See-saw protocol for Doppler cooling of multilevel systems with coherent pulse trains, Intern. Review Atom. Molec. Phys., (01 2013): 0. doi:
<b>TOTAL:</b>	<b>4</b>

Number of Papers published in peer-reviewed journals:

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(b) Papers published in non-peer-reviewed journals (N/A for none)

Received      Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

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(c) Presentations

Number of Presentations: 0.00

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received      Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received      Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

### (d) Manuscripts

Received

Paper

03/18/2014	4.00	Ekaterina Ilinova, Jonathan Weinstein, Andrei Derevianko. Stimulated cooling of molecules on multiple rovibrational transitions with coherent pulse trains, PHYSICAL REVIEW A (10 2012)
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**TOTAL: 1**

**Number of Manuscripts:**

## Books

Received

Paper**TOTAL:**

## Patents Submitted

## Patents Awarded

## Awards

## Graduate Students

NAME \_\_\_\_\_

PERCENT\_SUPPORTED

**FTE Equivalent:**

**Total Number:**

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### Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
New Entry	0.00
Ekaterina Illinova	1.00
<b>FTE Equivalent:</b>	<b>1.00</b>
<b>Total Number:</b>	<b>2</b>

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### Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

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### Names of Personnel receiving masters degrees

<u>NAME</u>
Mahmoud Ahmad
<b>Total Number:</b>

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### Names of personnel receiving PHDs

<u>NAME</u>
<b>Total Number:</b>

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### Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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### Sub Contractors (DD882)

### Inventions (DD882)

### Scientific Progress

During this short 9-month grant we have theoretically explored a variety of novel techniques of using frequency combs for laser cooling and manipulation of quantum atomic and molecular systems. The findings are well documented in five attached reprints.

To reiterate:

- = we developed basic understanding, theoretical models, and analytical/numerical solutions to the problem of comb cooling of two, three and multilevel systems
- = We proposed ``velocity combs": atomic beams with a series of equidistant sharp teeth (mK wide). They could be used in collision studies or in atom interferometry.
- = We proposed a technique of stimulated cooling of molecules on ro-vibrational transitions with frequency combs.

### Technology Transfer